Delta Ecological Survey (Phase I):
Nonindigenous aquatic species in the Sacramento-San Joaquin Delta, a Literature Review

Submitted by:
Theo Light, Postdoctoral Researcher
Ted Grosholz and Peter Moyle, Project Managers
Department of Environmental Science and Policy
University of California at Davis
One Shields Avenue
Davis, CA 95616

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SUMMARY

Introductions of nonindigenous aquatic species (NAS) are a significant threat to estuarine and freshwater systems worldwide. Discharge of ballast water is an important pathway of these invasions, leading to national, international, and state efforts to regulate ballast water discharge and document the current status of NAS and rate of introductions into major port systems such as the Sacramento-San Joaquin Bay-Delta and river system. This project examines the sources, vectors, and extent of invasions into the Delta, the most upstream portion of the San Francisco Estuary system. We reviewed the literature on NAS in the Delta, developed a database format to store, organize and present this information, and analyzed the sources, vectors, and time-sequence of introductions of both estuarine and freshwater NAS currently found in the Delta.

We identified 193 definite or probable introductions into the Delta (69 plants, 89 invertebrates, and 35 vertebrates), and 25 cryptogenic species (17 phytoplankton species, 1 plant, and 7 invertebrates). Invertebrate introductions have increased over time since the 1850s, while introductions of fully aquatic plants and vertebrates show little trend with time, and marsh/riparian plant introductions have declined. Sources of introduced organisms are diverse, with most plants native to Europe or South America, invertebrates largely from either eastern North America or Asia (with Asian sources dominating in recent decades), and most vertebrates native to eastern North America. Pathways of introductions into the Delta are also diverse, and vary considerably among taxa: most plants represent either agricultural weeds or escaped ornamentals, vertebrates have largely been introduced via deliberate stocking (or are unintentional releases associated with stocking), while invertebrates are more likely to have reached the Delta via ship fouling or ballast water releases, along with unintentional releases with fish stocking and individual releases of aquarium, bait or food organisms.

Freshwater and estuarine NAS have distinct introduction histories, with estuarine organisms predominantly reaching the Delta via shipping-related vectors from sources in Europe and Asia, while freshwater organisms are largely from the Americas and Europe and are more likely to be introduced by fish stocking, agriculture, and individual releases. In recent decades, estuarine NAS have become increasingly associated with ballast water and Asian sources, while both the vectors and sources of freshwater NAS are becoming more diverse. Because freshwater NAS are dominant in the Delta, this suggests that ballast water regulation alone will not halt invasions into this system; reducing the rate of freshwater invasions will also require management of numerous diffuse and hard-to-control vectors.

Summary of Recommendations:

- We recommend more thorough sampling, preferably on an annual basis and at least every 2-3 years, of several habitats and groups that are undersampled by current efforts. In particular, we recommend increased sampling of shallow water habitats, including small channels and sloughs, the margins of larger channels, and temporary pools; of vegetation; and of fouling communities. Improved taxonomic work is needed particularly for species-level identification of larval insects and of phytoplankton and periphyton.
- Continued assessment is needed of the effectiveness of ballast water control in slowing the rate of invasions into the upper estuary.
- We also suggest increased attention be given to other vectors which commonly bring freshwater species to the upper estuary, including aquarium and bait releases, recreational boating and fishing, and garden and ornamental pond escapes.

CHAPTER 1: Introduction

Introductions of nonindigenous aquatic species (NAS) and their social, economic, and ecological effects are increasing. Introductions are considered the second most important threat to biodiversity (after habitat modification) in North America (Wilcove et al. 1998). Coastal marine, estuarine, and tidal freshwater systems are among the most invaded systems worldwide, though the extent of the invasion threat to these systems has been only relatively recently recognized and is still being documented (e.g., Carlton & Geller 1993; Cohen & Carlton 1995; Ruiz et al. 1997, Grosholz 2002). Discharge of ship ballast has been identified as a significant pathway for NAS introductions into these systems (Carlton & Geller 1993, Ruiz et al. 2000). The US Coast Guard implemented a voluntary ballast water exchange program in 1999 under the National Invasive Species Act of 1996. Evaluation of the efficacy of these guidelines in reducing introductions of NAS requires that baseline information be developed on the NAS currently present in estuarine systems.

The biological integrity of the aquatic resources of the Sacramento-San Joaquin River system is essential to the protection of anadromous and estuarine fishery resources of enormous importance to California. This river system drains some 40% of the land area of California, and provides at least a portion of the drinking water to more than 50% of Californians. The rivers and estuary have been dramatically altered in the last 150 years both physically and biologically through urbanization, draining and conversion of wetlands to agriculture, withdrawal and diversion of significant proportions of its annual flow for irrigation and urban water supply, and the introduction of large numbers of NAS which now dominate virtually every habitat sampled in the lower river and estuary (CDFG 1995; Cohen & Carlton 1995). Understanding the sources, extent and effects of invasions into this system, and slowing the rate of future invasions, is an essential component of ongoing efforts to restore the Bay-Delta and river systems.

Project Background Information

This project was initiated in January 2003, and has been managed and carried out by a team of researchers at the University of California, Davis. Ted Grosholz and Peter Moyle were co-principle investigators for the project, responsible for administration of the budget and work plan. Theo Light was hired in February 2003 as a postdoctoral researcher, and has been responsible for carrying out the database development, literature search, data analysis, and report preparation. Our technical advisory committee (TAC) was made up of scientists familiar with the Delta and its native and nonindigenous species, who were consulted for their advice and taxonomic expertise at various stages of the project. The TAC included: Andy Cohen (San Francisco Estuary Institute), Lee Mecum (California Department of Fish and Game), Wayne Fields (Hydrozoology), Lars Anderson (UC Davis), Susan Ellis (California Department of Fish and Game), Kim Webb (US Fish and Wildlife Service), and Erin Williams (US Fish and Wildlife Service).

Project Objectives

The purpose of this agreement was to survey available information regarding NAS in the Sacramento-San Joaquin Delta and river system (SSJR), in order to characterize the extent, sources, and vectors of invasions and provide a baseline for evaluating the rate of species introductions. The specific project objectives were to:

- Develop a database for NAS (known or suspected) identified through a literature search that includes the timeframe of introductions, native and source regions of introduced species, modes of introduction, geographic distribution, ecological and economic impacts, taxonomy and synonymy, references and other relevant information.
- Review existing literature (published and unpublished) on NAS that have invaded the SSJR to furnish the information relevant to the database.
- Summarize the findings of the literature survey, and provide: (1) an analysis of current diversity patterns, areas of NAS origin, and mechanisms of NAS delivery to the SSJR; (2) recommendations regarding the need for field surveys of taxa and areas poorly represented in the literature; (3) recommendations for a continuous monitoring program to assess future NAS invasions and changes from historical conditions; and (4) an assessment of the effectiveness of ballast water management and other vessel management guidelines issued and regulations promulgated under NISA and the State of California for limiting NAS introductions into the SSJR.

CHAPTER 2: Methods

Study Area

This work reports on NAS present in or adjacent to the Sacramento-San Joaquin Delta, the mostly freshwater upstream portion of the San Francisco Estuary system (CDFG 1995). The Delta is formed at the confluence of the Sacramento and San Joaquin Rivers, and encompasses about 1100 mi^2 of intersecting channels and islands of former tidal marsh, now mainly converted to agriculture. The legal Delta (CDFG 1995) encompasses the area from Chipps Island just downstream of the confluence of the mainstem Sacramento and San Joaquin Rivers upstream to the limits of tidal waters, including the lower reaches of the Sacramento, Cosumnes, Mokelumne, Calaveras and San Joaquin Rivers, as well as innumerable smaller streams, channels, and sloughs (Fig. 1).

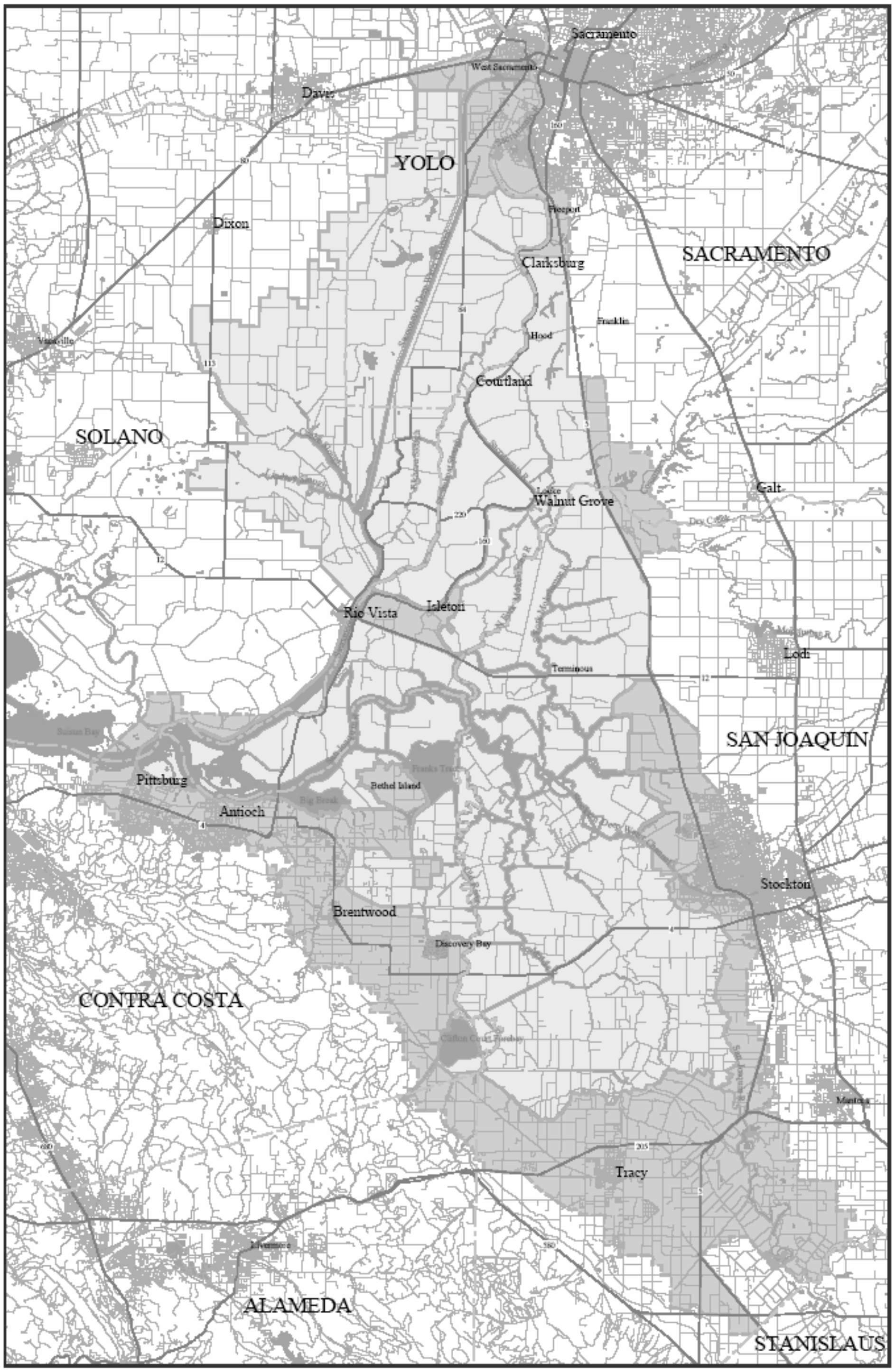


Figure 1: The Sacramento-San Joaquin Delta. Shaded area is the "legal delta," the area of our study. (Image from the California Department of Water Resources.)

Literature review and database

We conducted an extensive review of published and unpublished literature and databases to compile an up-to-date listing, including available ecological information, of known or suspected species introductions into the SSJR. Data for each species were entered into a relational database developed in Microsoft Access. The database was based (in part) on two models: the SERC_Invasions database of the National Ballast Water Clearinghouse (Smithsonian Ecological Research Center 2004), and the LCRANSdb database of the Lower Columbia River NAS Survey (Waldeck et al. 2003), though it was extensively modified from both of these to fit the goals and limitations of the current project. A complete description of the database structure can be found in Appendix A. Following is a listing of the categories of data included in the database:

Taxonomy: Scientific and common names, authority and date, synonyms, hierarchical classification. Taxonomic information generally was obtained from the Integrated Taxonomic Information System (www.itis.usda.gov). Occasionally names and taxonomy follow sources other than ITIS when we considered these sources to be more reliable and/or current than those referenced in ITIS. For species not appearing in ITIS, taxonomic data were derived from the most recent authoritative source available.

Identification: Image and description (when available), commonly misidentified species.

Invasion history: Dates and locations of first collections in the Delta, central California, and western North America; probable invasion date (range); source and native regions; likely introduction vector(s); invasion and residence status; a brief narrative of the invasion history of the species; invasion history in other locations.

Ecology: When available, we included basic ecological information regarding body size; general abundance in the Delta; lifespan; fecundity; environmental tolerances (salinity, temperature, dissolved oxygen); trophic status and feeding mode; common prey and predator species; common parasites, commensals, and host species. These data were generally most available for vertebrates, particularly fishes.

Habitats: Here we followed the SERC model fairly closely and used (with some modification) their habitat classifications for "horizontal" (e.g., riparian, marsh, vegetation, open water, etc.) and "vertical" (e.g. benthic, littoral, pelagic, etc.) habitat. Separate habitat data can be entered for different life stages (e.g. juvenile and adult fishes), though this was not always done. Based on the center of abundance of the species within the estuary, we categorize species as "freshwater" or "estuarine"; the estuarine category is further subdivided into "regular in the Delta" (those species which are collected nearly annually in the Delta, but which have their center of abundance further downstream) and "rare in the Delta" (those species which have been collected only a few times in the Delta, but which are more abundant downstream).

Distribution: We provided a generalized picture of species distribution within the Delta and the lower reaches of its major tributaries.

Collections: For some species, we provided detailed information on collection sites, range of dates species were collected, frequency and densities. This was a late addition to the database to facilitate later expansion, and data are currently included for only a selection of benthic species.

Invasion impacts: We included a narrative account of known and suspected ecological and economic impacts of each NAS for which this information is available.

References: We provided complete citation information for all references, including abstracts (when available electronically) and keywords, with links to all referenced species appearing in the database.

Sources

Sources for the data reported here fall into three main categories: (1) peer-reviewed published literature, obtained through the UC Davis Library and inter-library loan service, and in some cases online; (2) the "gray" literature, consisting mainly of government reports and some student theses, obtained as above as well as through personal contacts with agency biologists; and (3) online databases, a category of increasing importance both locally and nationally. Preliminary lists of nonindigenous and cryptogenic species compiled from these sources were then submitted to members of the TAC in their respective areas of expertise for corrections and clarification. We were fortunate to follow earlier major efforts to document the NAS and cryptogenic species of the San Francisco Estuary system; Cohen & Carlton's (1995) study was a foundational source of information and references on all taxonomic groups. Additional notable or particularly comprehensive sources for each of the major taxonomic groups include:

Phytoplankton: Laws (1988) gives a listing and brief ecological information on 273 diatom species identified from both surface sediments throughout the estuary and late Pleistocene (Sangamon) sediments beneath south San Francisco Bay. Current distribution and abundance of phytoplankton species were obtained from the Interagency Ecological Program's phytoplankton database (IEP 2003).

Vascular plants: We assembled a number of plant lists from both published and unpublished sources, including lists for Jepson Prairie (Witham 1996), the Sacramento Regional County Sanitation District bufferlands (SRCSD 2003), the Yolo Bypass Wildlife Area (Babba 1998), Delta Meadows River Park (Bowcutt 1996), and the lower Sacramento River near Collinsville (Willoughby & Davilla 1984). Two major sources of additional site records were the CalFlora plant occurrence database (Calflora 2003) and the UC-Jepson Specimen Management System for California Herbaria ("SMASCH", Jepson Herbarium 2003), both of which are available online. The latter two were particularly important sources for historic collections, allowing us to identify earliest collection dates in California and the Delta for most plant species. Ecology, habitat, and invasion history and impact data were derived mainly from Hickman (1993) and DiTomaso & Healy (2003), wetland indicator status from USFWS (1997), and introduction status elsewhere in the US from the USDA PLANTS online database (USDA 2002).

Invertebrates: Beyond what is included in Cohen & Carlton (1995), information on invertebrates in the Delta is relatively dispersed through the published and unpublished literature. The IEP database (benthos and fisheries, which includes many cnidarians and decapods) was the single most important source of distribution and abundance data for benthos and selected other groups (IEP 2003). Although zooplankton and mysids are also sampled under the IEP, these data are not yet available online, and we relied more heavily on published reports, particularly the periodic reports in the IEP Newsletter. Ecological data, when available, came from published papers and reports as well as more generalized sources (i.e., the freshwater invertebrate text of Thorp & Covich 2001).

Fishes: Moyle (2002) was our main source for information on life history, ecology, habitat, and invasion impacts; some additional ecological and taxonomic data were derived from FishBase (2003), an online database of fish ecology, taxonomy, and life history. Dill & Cordone (1997) give exhaustive accounts of the introduction histories of most nonindigenous fishes in California. Distribution and abundance within the Delta were obtained from the IEP fisheries database (IEP 2003).

Criteria for inclusion

Residence status: We included in the main table of Delta NAS only aquatic species that are resident to or occasionally (at least once, for lower estuary residents) found within the boundaries of the legal Delta, as described above. We also include species that regularly migrate through the Delta; for most of these, at least one life stage makes extensive use of the Delta. A secondary table gives abbreviated information on NAS present in areas adjacent to the Delta, which could conceivably invade the Delta sometime in the future. For animals, we include only fully aquatic species, here ignoring the many essentially terrestrial reptiles, birds and mammals that can occasionally be found in Delta wetlands (Cohen & Carlton 1995). Plants are limited to species which are usually or always found in wetlands, those rated facW or above in Region 9 on the US Fish and Wildlife Service wetland indicator scale (USFWS 1997). For some analyses we further separate plants into fully aquatic (floating or emergent plants commonly found in standing water) and marsh/riparian species. This distinction was made based on habitat descriptions given in either DiTomaso & Healy (2003) or Hickman (1993).

Invasion status: Determining whether a species is native or introduced to a particular region is not always clear-cut, particularly for groups that do not fossilize well or for which regular sampling has begun relatively recently. Criteria for determining native or introduced status have been extensively discussed elsewhere (Chapman & Carlton 1991, 1994; Cohen & Carlton 1995; Ruiz et al. 1997). We followed the determinations of Cohen & Carlton (1995) for most species included in that report; for those not included we applied the criteria of Chapman & Carlton (1991, 1995). We assigned species to one of three categories: (1) **Definite invaders** are species for which most lines of evidence point to their introduced status, and there is broad consensus among experts that they are introduced to the SSJR. Often these are species for which there is a historical record of the introduction and/or the native and introduced ranges of the species are well-defined. (2) **Probable invaders** are those species for which several lines of evidence point to their introduced status, but there is some disagreement among experts regarding their introduced status in the SSJR and the extent of their native range. (3) **Cryptogenic** species are those that cannot be definitively assigned as native or introduced. In many cases these are species for which the taxonomy is not sufficiently resolved to make a determination. Other species assigned to this category include "cosmopolitan" species in poorly studied groups for which there is some evidence that they may have a long association with mechanisms of human transport (e.g., many oligochaetes; Timm 1980). The listing of cryptogenic species in the current work is conservative rather than exhaustive.

Vectors

As much as possible, we used the vector names, abbreviations, and categories in the SERC_Invasions database. We changed the categories for certain vectors to suit the emphases of our analysis; for example, the vector "discarded bait" was moved from the category "Fisheries" to our category "Individual Releases". Vectors we use here which are not found in SERC (2004) are AQ-aquaculture escapes, BC-biocontrol release, ErC-erosion control, EC-escape from cultivation, RecB-recreational boating/fishing, and RI-released by individual (unofficial plants other than bait or aquarium releases). Vectors in SERC (2004) that do not appear here include AP-aquatic plant shipments, CN-canal, and ND-natural dispersal. (Although some NAS previously introduced to northern California or the West may have reached the Delta by means of "natural dispersal", the original invasion vector was of more interest to our analysis.) Vectors appearing in this report are given in Table 1.

Table 1: Names, abbreviations, and categories of vectors bringing NAS to the Delta.

Vector Category	
Vector abbreviation & name	
Agriculture	
AW	Agricultural Weed
ErC	Erosion Control
EC	Escape from cultivation
Biocontrol	
BC	Biocontrol release
Fisheries	
AQ	Aquaculture escape
FA	Fisheries Accidental (not Oyster)
FI	Fisheries Intentional
OA	Oyster Accidental
OI	Oyster Intentional
Individual releases	
DiB	Discarded Bait
GE	Garden Escape
PR	Pet/Aquarium Release
RecB	Recreational Boating/Fishing
RI	Released by Individual
Shipping	
BW	Ballast Water
DrB	Dry Ballast
FC	Fouling Community
Research	
SE	Scientific Escape
Unknown	
UnkV	Unknown Vector

Analysis

We examined patterns in the sources, vectors, and time-sequence of invasions into the SSJR, restricting our analysis to species considered to be definite or probable invaders. Our analysis of invasion sources refers to the original source (native region) of the NAS, even if this was not the immediate source of the invasion. Native regions can usually be documented with more certainty than the immediate invasion source, and this analysis adds to our understanding of global invasion patterns. Similarly, we focus on the invasion vector bringing the species to central California, even if it subsequently reached the Delta by natural spread.

CHAPTER 3: Results

General

We documented a total of 193 definite or probable introductions into the Delta (Appendix B), including 69 plants, 89 invertebrates, and 35 vertebrates (32 fishes, one amphibian, one reptile, and one mammal). Of these, the majority (139 species; 72%) were primarily freshwater species; of the estuarine species, 31 (16%) are regularly encountered in the Delta, while 23 (12%) are occasional visitors, with only one or a few collections in the west Delta.

We listed 25 species as cryptogenic in the Delta (Appendix C), including 17 phytoplankton species, 1 plant, and 7 invertebrates. As noted above, this list is conservative: many more invertebrates, including (as an example) most of the cosmopolitan oligochaetes in the estuary, could arguably be listed as cryptogenic (e.g., CDFG 2003).

Vascular plants

Nearly all of the 69 species of nonindigenous plants in the Delta have freshwater affinities (67 species; 97%); the two estuarine species are regularly found in the Delta as well as Suisun Marsh and further downstream. Most plants fall into the marsh/riparian category (51 species; 74%), while 18 are fully aquatic.

Most plants introduced to the Delta were native to Eurasia (48 species; 70%), particularly Europe; several of these occur in North Africa as well (Fig. 2). Only 7 plants (10%) were native to eastern or central North America, though many of the European invaders probably reached California from eastern North America populations. Eleven plants (16%) were native to South America, and may have been imported either directly from that continent or from eastern North America (water hyacinth, *Eichhornia crassipes*, for example, was first introduced to the US in New Orleans) (Cohen & Carlton 1995). The remaining plants were native to Africa (2 species) and the south Pacific Islands (1 species).

Agriculture-related vectors (escaped cultivars, agricultural weeds, and plants used for erosion control) account for 36 (52%) of the introduced plants in the Delta (Fig. 3). Another 13 (19%) represent escaped ornamentals, which we grouped with aquarium releases (3 species; 4%) as individual releases for analysis. One species (curly pondweed, *Potamogeton crispus*) was apparently introduced accidentally with stocked fishes. At least one (brassbuttons, *Cotula coronopifolia*) and possibly two others may have been introduced with solid ballast. Fifteen plants could not confidently be assigned to any vector, and were classed as unknown, though possible alternate vectors were posited for some of these.

Invertebrates

Not quite half of the 89 nonindigenous invertebrates in the Delta are mainly freshwater residents (44 species; 49%). Of the estuarine species, 22 (25%) are regularly found in the Delta while 23 (26%) are only rarely encountered. A diverse group, the invertebrate NAS are dominated by arthropods (43 species; 62%), annelids (17 species; 25%) and molluscs (10 species; 14%) (Appendix B).

Most invertebrate NAS were natives of either east Asia (33 species; 36%) or eastern North America (33 species; 37%), reflecting dominant patterns of both shipping and oyster stocking (Fig. 2). The remainder are natives of Europe (9 species; 10%), Australia (4), South America (2), Africa (1), or were of unknown origin (7).

Shipping was the most likely vector for half the invertebrate invaders in the Delta (44 species; 50%), including 38 probable ballast water invaders, 9 species associated with ship fouling, and one with solid ballast (Fig. 3). Thirty-eight invertebrate NAS (42%) were associated with fish or oyster stocking, all but one of these (the deliberately stocked signal crayfish, *Pacifastacus leniusculus*) being non-target, "accidental" species. Remaining vectors include biocontrol releases (2 species), individual releases of food or aquarium species (4), likely hitchhikers on recreational boats or fishing gear (2), scientific escapes (1), and unknown vectors (1).

Vertebrates

Vertebrate NAS, like plants, were dominated by freshwater species (29 species; 83%). The six estuarine species (all fishes) are regularly found in the Delta; two of these (American shad, *Alosa sapidissima* and striped bass, *Morone saxatilis*) are anadromous species that make extensive use of freshwater for part of their life cycle (Moyle 2002).

Most introduced vertebrates in the estuary are natives of eastern and central North America (29 species; 83%) (Fig. 2). Two (common carp, *Cyprinus carpio* and goldfish) are of Eurasian origin, though the source of introduced populations in the Delta is eastern North America or possibly, in the case of goldfish, Hawaii. The three gobies and one stocked fish (wakasagi, *Hypomesus nipponensis*) are natives of east Asia, and reached the Delta from their native range (Dill & Cordone 1997).

Fisheries-related vectors are responsible for 81% (26 species) of the nonindigenous fishes found in the Delta (Fig. 3). The major single vector of fish introductions was deliberate stocking for sport or forage (22 species; 69%). Two additional species (bigscale logperch, *Percina macrolepida* and rainwater killifish, *Lucania parva*) were probably introduced accidentally along with deliberately stocked fishes or oysters, while red shiner (*Cyprinella lutrensis*) has been stocked elsewhere in California but probably reached the Delta via its use as a baitfish. Blue catfish (*Ictalurus furcatus*) have been stocked in San Diego County, but most likely reached northern California and the Delta as escapes from aquaculture facilities in the Central Valley. Two species (western mosquitofish, *Gambusia affinis* and inland silverside, *Menidia beryllina*) were deliberately released for biocontrol purposes, one (goldfish, *Carassius auratus*) is an aquarium release, and the final three, all estuarine gobies, are believed to have reached the estuary via ballast water or ship fouling (Dill & Cordone 1997; Cohen 1998).

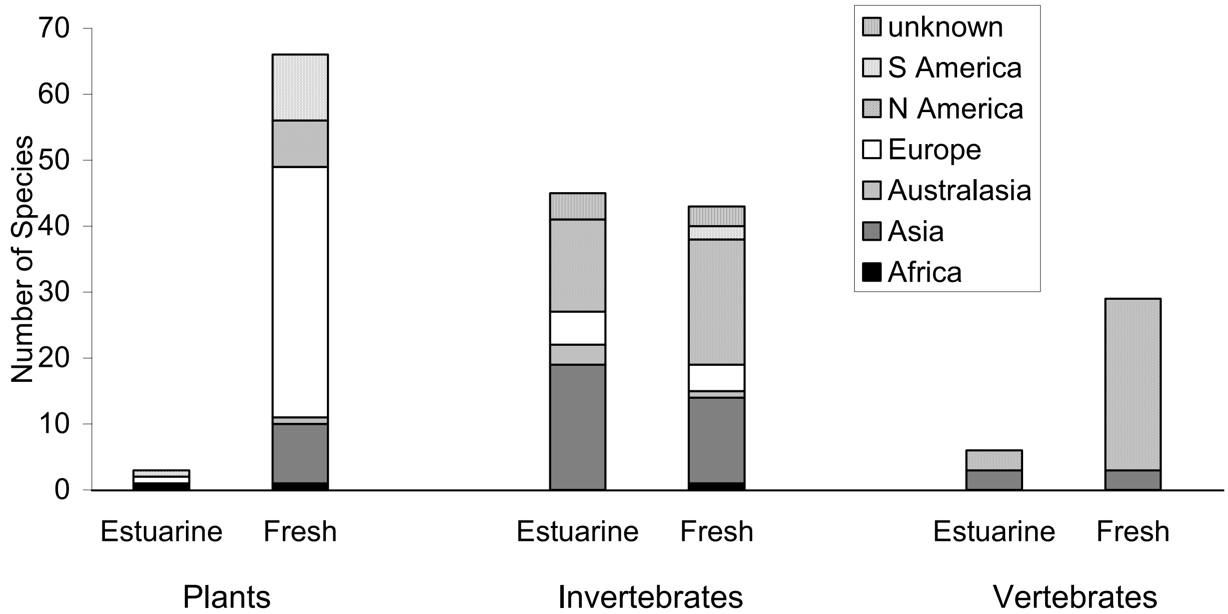


Figure 2: Continental origins of the three major groups of Delta NAS, contrasting estuarine and freshwater species.

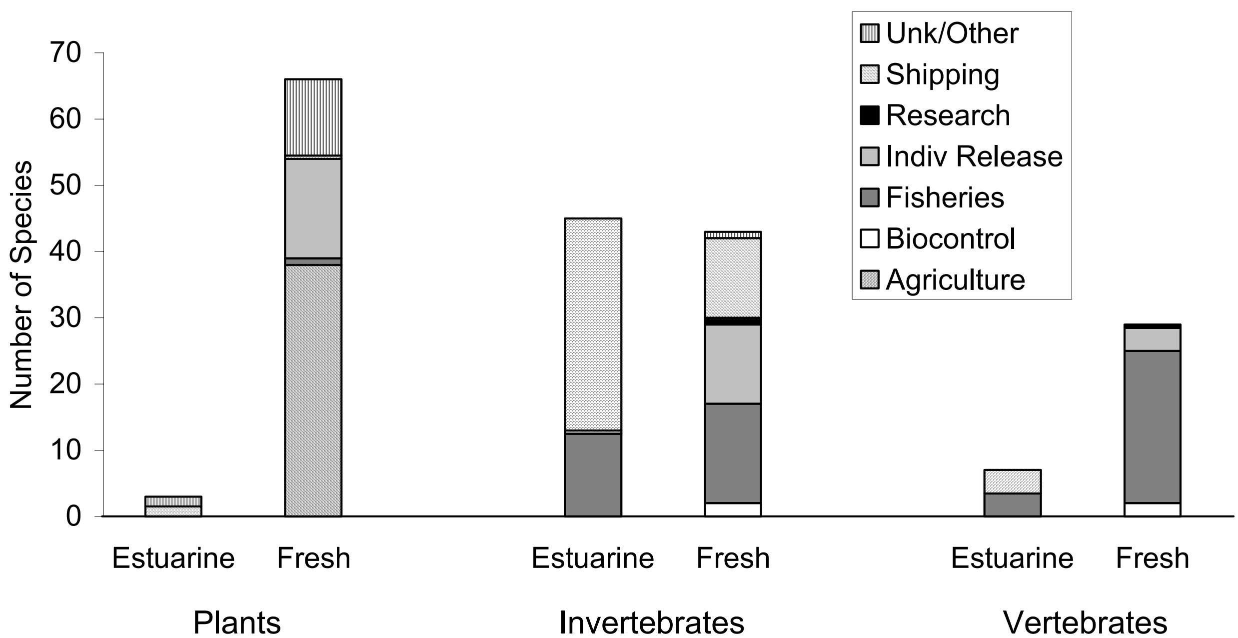


Figure 3: Vectors bringing NAS plants, invertebrates, and vertebrates to the Delta, contrasting estuarine and freshwater species.

The three non-fish vertebrates introduced to the Delta represent a pet release (common slider, *Trachemys scripta*) and two organisms farmed for meat and fur (bullfrog, *Rana catesbeiana* and muskrat, *Ondatra zibethicus*). Bullfrogs have also been imported to California for scientific study and instruction, a possible secondary vector (Cohen & Carlton 1995).

Time-frame of introductions

In contrast to the whole-estuary analysis of Cohen & Carlton (1995), overall introductions into the Delta per time period have not increased since the 1880s (Figure 4a). This general result, however, obscures the steady increase in invertebrate introductions and a decline in the rate of plant introductions (Figure 4a). If plants are limited to the fully aquatic species, which have introduction vectors more similar to those of other species in the estuary (i.e., they are less dominated by agriculture-related vectors), then some increase over time in total introductions is evident (Figure 4b). However, this increase is still almost entirely driven by the increasing rate of documented invertebrate introductions. Some of this increase in recent years can probably be attributed to more thorough sampling and more detailed taxonomy, leading to an increasing rate of discovery.

Sources & vectors of freshwater and estuarine introductions

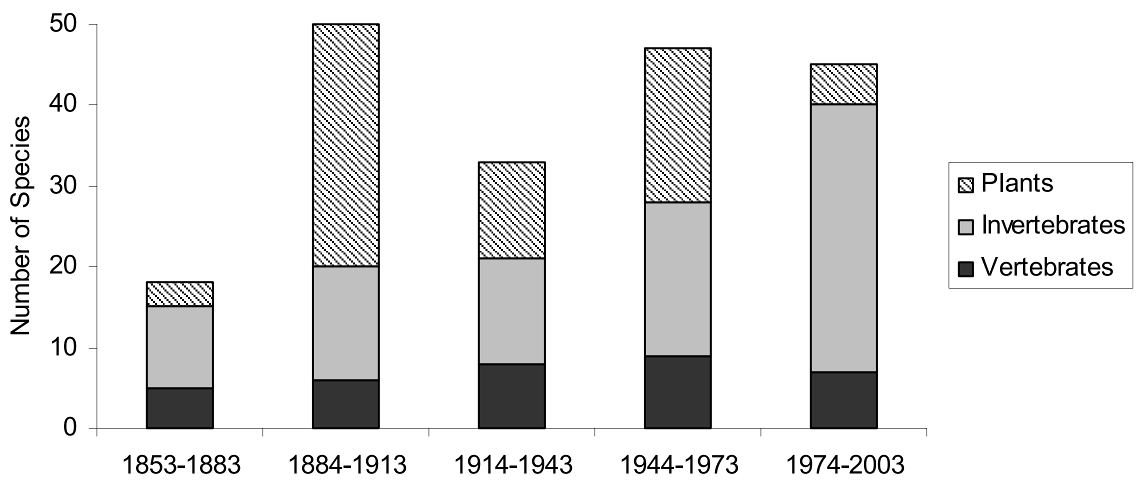
Sources: Native regions of Delta NAS differ between estuarine and freshwater species, with estuarine species predominantly from Asia and Europe while freshwater species are mainly from North America and Europe and have more diverse origins overall (all species: $\chi^2 = 22.2$, df = 6, P = 0.0011, Fig. 2; excluding marsh/riparian plants: $\chi^2 = 16.9$, df = 6, P = 0.0096). This is largely due to the differences among taxonomic groups, since the plants and vertebrates are more associated with freshwater, while half the invertebrates are estuarine. Native regions differ significantly among taxonomic groups, with plants predominantly from Europe, invertebrates from Asia and North America, and vertebrates from North America (all species: $\chi^2 = 121.3$, df = 12, P < 0.0001; excluding marsh/riparian plants: $\chi^2 = 62.6$, df = 12, P < 0.0001, Fig. 2). For invertebrates, the only taxonomic group with enough estuarine species for comparison, native regions do not differ between estuarine and freshwater species ($\chi^2 = 7.3$, df = 6, P = 0.29, Fig. 2).

Sources of invaders have changed through time, with Asia increasing in importance and Europe and North America decreasing, particularly for estuarine species (all species: $\chi^2 = 47.6$, df = 16, P <0.0001; excluding marsh/riparian plants: $\chi 2 = 39.3$, df = 16, P = 0.001; Africa and Australia excluded to meet assumptions of the Chi-square test; Fig. 5). While Asia emerges as an increasingly important source for estuarine NAS, the sources of freshwater NAS appear to be growing more diverse, though eastern North America remains the most important source overall.

Vectors: Vectors also differ between estuarine and freshwater NAS, with estuarine species much more likely to arrive via shipping, while freshwater species are more associated with agriculture, fisheries, or individual releases (all species: $\chi 2 = 83.7$, df = 6, P <0.0001; excluding marsh/riparian plants: $\chi^2 = 53.2$, df = 6, P < 0.0001; Fig. 3). This is partly, but not entirely, due to the differences in dominant vectors among taxonomic groups. Considering invertebrates separately, estuarine species are still significantly more likely to arrive via shipping, while sources of freshwater species are quite diverse ($\chi^2 = 19.5$, df = 5, P = 0.0015; Fig. 3).

Vectors bringing NAS to the Delta have changed through time, with shipping increasing in importance and fisheries decreasing for both freshwater and estuarine species, while individual releases have increased and agriculture-related vectors have decreased for freshwater species (all species: $\chi^2 = 91.3$, df = 24, P <0.0001; excluding marsh/riparian plants: $\chi 2 = 73.7$, df = 24, P <0.0001; Fig. 6). While shipping has become nearly the exclusive vector bringing estuarine NAS to the Delta, the vectors, like sources, of freshwater NAS have grown increasingly diverse, particularly in the last three decades (Fig. 6).

a.



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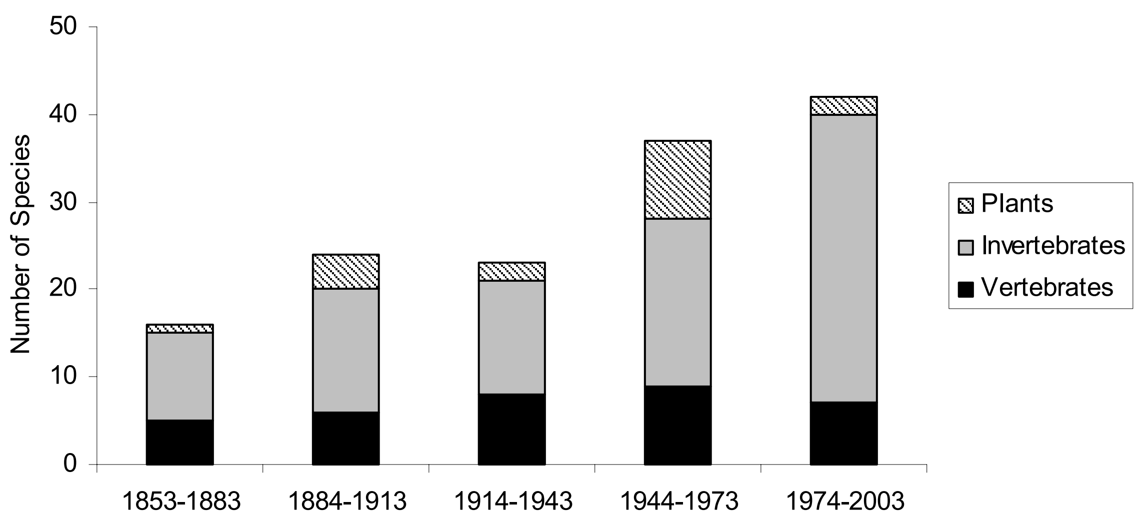

Figure 4: Changes over time in the rate of introductions of the major taxonomic groups of Delta NAS. (a) All species; (b) excluding marsh and riparian plants.

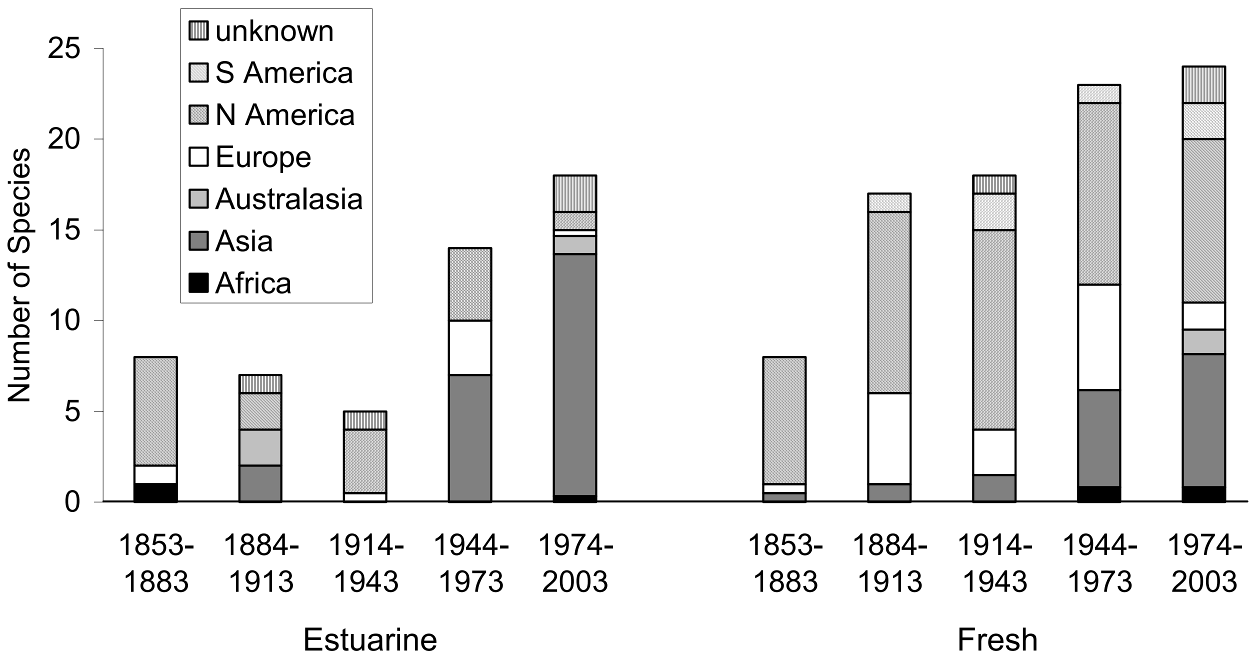

Figure 5: Changes over time in the native origins of estuarine and freshwater NAS in the Delta (this figure includes fully aquatic plants only).

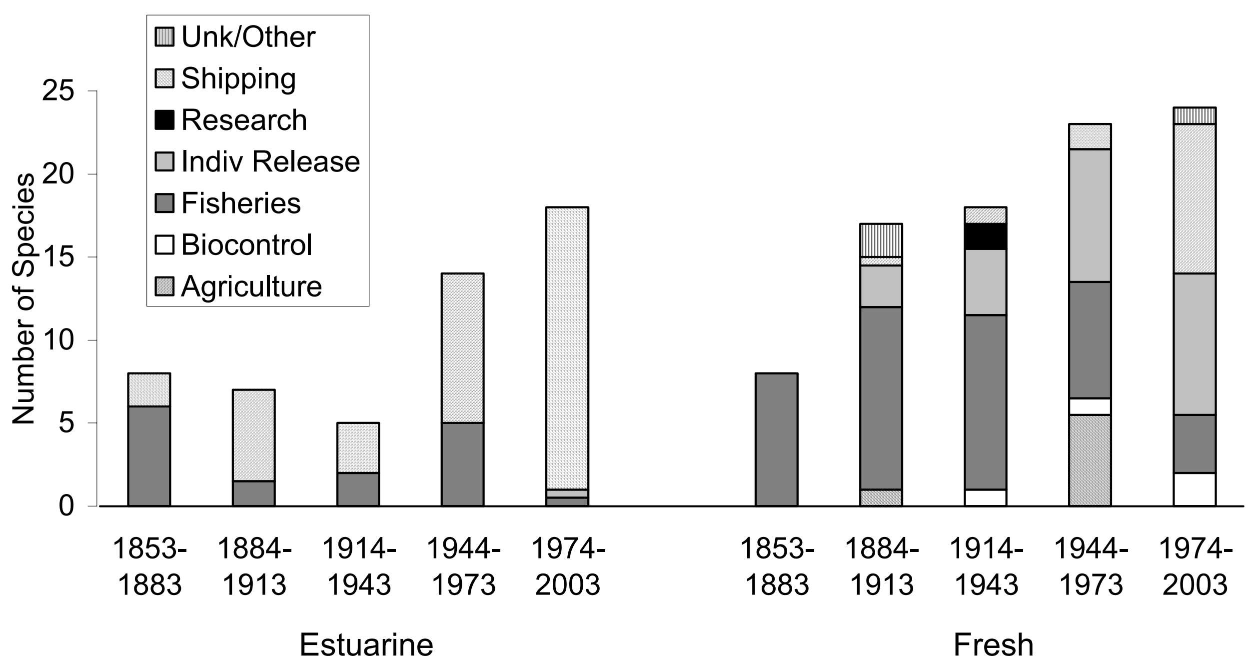

Figure 6: Changes over time in the vectors bringing estuarine and freshwater NAS to the Delta (this figure includes fully aquatic plants only).

CHAPTER 4: Conclusions

The Sacramento-San Joaquin Delta, like the lower estuary, is a highly invaded system. In addition to the high diversity of nonindigenous species, most sampled communities are dominated in both numbers and biomass by NAS. For example, the 2002 and 2003 summer townet surveys of juvenile fishes in upper estuary, 90% of fishes captured in 2002, and 88% in 2003, were nonindigenous to the Delta (Bryant 2003). Eight years (1992-99) of sampling a wide variety of habitats in the south Delta revealed a fish community consisting of fewer than 5% native individuals (Feyrer & Healy 2003). In benthic sampling throughout the Delta, typically 95% or more of the biomass consists of NAS, largely *Corbicula* (W. Fields, pers. comm.). The most abundant copepod and mysid species in the Delta in most seasons are also nonindigenous (IEP 2003).

The introduction histories of estuarine and freshwater NAS in the Delta are clearly divergent. For example, most fishes have freshwater affinities and were deliberately introduced in the late 1800's and early 1900's, mainly from eastern North America (Dill & Cordone 1997). Along with these introductions came a number of unintended species, including fishes, invertebrates, and aquatic plants. In contrast, many of the estuarine invertebrate and fish invaders reached the Delta in ballast water, solid ballast, and attached to vessel hulls (Cohen & Carlton 1995). In the most recent three decades, estuarine NAS have become increasingly associated with ballast water and Asian sources, while both the vectors and sources of freshwater NAS are becoming more diverse. Individual releases, shipping, and biological control have increased in importance for freshwater NAS.

Effectiveness of ballast water regulation

Much management attention continues to be focused on minimizing ballast water as a source of introductions into estuaries. The National Invasive Species Act of 1996 established voluntary guidelines for ballast water exchange and management, effective in 1999 for all vessels entering US waters from beyond the exclusive economic zone (EEZ). As of January 2004, the California Marine Invasive Species Act has required mid-ocean ballast water exchange prior to entering California ports.

Shipping-related vectors, particularly ballast water, are presently the most important category of vectors bringing NAS to the Delta. In the last 30 years, about half (18 of 37 species) the new NAS regularly encountered in the Delta (freshwater and regularly resident estuarine species) were probably introduced via ballast water. This invasion vector has also seen the greatest increase in recent years. Assuming the above-cited regulations are relatively effective, we should expect significant declines in the rate of new invasions into the Delta in the future.

For primarily freshwater species, however, the diverse category of individual releases is about coequal with shipping as a vector of new invasions into the Delta. This vector has increased in importance over the last 60 years, and can be expected to continue to increase in the future, partially canceling expected gains from ballast water regulation. Human population increases in central California, as well as growing popularity of recreational boating and fishing, aquariums and backyard water gardens, and the ease of importation of exotic species via the web (Padilla & Williams 2004) can be expected to drive this increase. This suggests that protecting the Delta from further freshwater invasions will require ongoing management of numerous diffuse and hard-to-control vectors.

CHAPTER 5: Recommendations

A. Sampling recommendations

Introduction

The Sacramento-San Joaquin Delta is, in many respects, a very intensively sampled system. The Interagency Ecological Program's Environmental Monitoring Program (IEP EMP) has regularly monitored the upper estuary since 1971 for zooplankton (currently 19 sites, 8 in the Delta), phytoplankton (11 sites, 7 in the Delta) and benthic invertebrates (10 sites, 6 in the Delta) (Mueller-Solger 2001). At least six separate sampling programs of the California Department of Fish and Game (DFG), Department of Water Resources (DWR), US Fish and Wildlife Service (FWS), and the University of California, Davis (UCD) sample fishes and selected invertebrates in and around the Delta and Suisun Bay. The earliest of these, DFG's Summer Townet Survey, was initiated in 1959, and the most recent, DWR's Yolo Bypass Study, began in 1998. All six are ongoing (IEP 2004).

Most of these sampling programs, however, have some shared limitations. Because most programs seek mainly to quantify population trends in relatively abundant species, they primarily focus on habitats and sampling regimes that can be sampled easily, quantitatively, and repeatably. Routine benthic, fisheries, and plankton sampling is largely carried out in midchannel habitats and over unstructured, unvegetated habitats. However, the highest diversity and abundance of species is often found in shoreline habitats or associated with aquatic vegetation or other cover, such as rip-rap (Chotkowski 1999; W. Fields, pers. comm.; R. Schroeder, pers. comm.). Other undersampled habitats and groups include fouling communities, temporary water bodies and small sloughs. We therefore recommend that sampling for NAS in the Delta be focused on these undersampled habitats and groups associated with them.

Furthermore, the spatial scale over which species assemblages of small benthic invertebrates vary is much smaller than that of either fishes or zoo/phytoplankton. With benthic invertebrates, you may see dramatic changes in which species are present (not just numbers) over scales of meters. IEP sampling for benthic invertebrates noted above (10 sites, 6 in the Delta) is similar in spatial extent to that for fishes and plankton, which vary over much larger scales. This limited spatial sampling has likely hugely underestimated benthic diversity. Since the scale of variation is 10 to 100 times smaller than for fishes and plankton, we recommend *at least* a ten fold increase in the number of sampling sites for benthic invertebrates, with a target of at least 100 sites around the Delta distributed among the habitats discussed below. Agency sampling has chosen convenient sites and species to examine changes in the system over time or to have an index of response to human activities. For the purposes of the current project, species lists do not need to be replicated frequently in time. An annual survey would be more than adequate and a survey every 2-3 years (if really thorough) would be acceptable.

Adequately sampled groups and habitats:

1. Fishes are probably adequately sampled in the estuary. The existing sampling programs are quite extensive and have successfully detected all of the recent fish introductions (shimofuri goby, shokihaze goby) in the upper estuary. Even though shallow-water, vegetated habitats are relatively undersampled for fishes (Chotkowski 1999), this has

probably resulted more in a mischaracterization of overall abundances than in missing species completely.

2. Zooplankton are probably adequately sampled in the estuary, with the exception of zooplankton associated with temporary water bodies and small sloughs as discussed below. While existing sampling programs do not sample shallow vegetated habitats, this again probably results mostly in mischaracterization of relative abundances, with vegetation-associated species appearing to be less common than they are.

Undersampled groups and habitats:

3. **Benthic infauna of shallow water habitats, including larval insects.** Since most benthic sampling has been done mid-channel, shallow, shoreline habitats should be sampled for benthic infauna. Mid-channel sampling misses most insect species, which tend to be associated with shallow water and/or vegetation. The taxonomic resources for insects will be a limitation, since it is difficult to determine what is native and what is not.
4. **Vegetation-associated invertebrates, including larval insects.** Because of sampling difficulties, vegetated areas are generally avoided in routine invertebrate sampling in the Delta and estuary. In a study of the invertebrate associations of native and introduced aquatic plants, Toft and others (1999, 2002) found three previously undetected nonindigenous invertebrates in the Delta (the amphipod *Crangonyx floridanus* and isopods *Caecidotea racovitzai* and *Asellus hilgendorfii*). This suggests that a comprehensive survey of invertebrates associated with both floating and emergent aquatic vegetation, particularly nonindigenous plant species, may turn up some additional nonindigenous invertebrates.
5. **Fouling communities.** There is no regular sampling program for fouling organisms in the Delta. Several non-indigenous freshwater fouling organisms (*Cordylophora caspia*, *Urnatella gracilis, Balanus improvisus*) are known mainly from studies of the Delta-Mendota Canal (Eng 1975), and are rarely, if ever, collected in routine benthic or other sampling (IEP 2004). Rapid assessment of nonindigenous species in estuaries typically focuses on fouling organisms because the habitat is easily sampled and often contains a significant component of nonindigenous organisms (Cohen et al 1998, 2001). Non-indigenous organisms are frequently associated with artificial substrates such as docks, pilings, floats, and buoys (Chapman & Carlton 1991). We recommend a thorough assessment of fouling communities in the Delta, particularly in and around the ports of Stockton and Sacramento and in heavily used recreational boating areas.
6. **Temporary (particularly fishless) habitats.** "Tidepools" in upper marshes, nearby vernal pools, and floodplain habitats are undersampled in the estuary; such habitats should be sampled for both zooplankton and benthos. Fishless habitats, in particular, may contain very different species than nearby permanent waters. Such habitats are inherently seasonal, and hence will need to be sampled in winter or spring as conditions warrant. Although repeated sampling of these habitats would be ideal to capture seasonal variations, even a single annual sampling could capture some otherwise unsampled species.
7. **Small channels and sloughs.** Many of these have overhanging vegetation and hence could be considered an extension of the shallow water/vegetated habitats mentioned

above. Small sloughs should be sampled for both zooplankton and benthos. Possible sites include Beaver Slough, Hog Slough, Sycamore Slough, Seventeen Mile Slough, Jackson Slough, Georgiana Slough, White Slough and the San Joaquin River south of Hwy 4 (Lee Mecum, pers. comm.).

8. **Phytoplankton and periphyton.** Phytoplankton have been relatively well sampled in the Delta (IEP 2004), but the taxonomy and biogeographic history of most groups are poorly known. While numerous species have been identified as cryptogenic, none have conclusively been determined to be nonindigenous (Cohen & Carlton 1995). This group merits more attention, though further sampling is probably not as important as consultation with taxonomic experts. Benthic algae and periphyton are not routinely sampled in the Delta, and should be assessed in any comprehensive survey, perhaps in conjunction with surveys of fouling invertebrates. Diatoms (with silicate structures) and other unicellular taxa such as foraminifera that fossilize well should be a priority, because there is the possibility of looking at core samples and inferring what was here in the past (this has already been done to some extent with forams). These could be sampled by benthic coring on a one-time basis with routine phytoplankton sampling carried out through IEP providing follow-up.
9. **Parasites and commensals.** Many species of parasites and commensals, many of them introduced, are no doubt associated with each of the free-living NAS in the Delta. These groups have been only sporadically investigated (e.g., Edwards & Nahhas 1968; Hensley & Nahhas 1975). While a thorough assessment of symbionts would no doubt add many species to the overall NAS list for the Delta, it would add little to our understanding of vectors and sources of invaders. Furthermore, the taxonomic resources for many of these groups are limited and scattered throughout the literature. Since there is little or no baseline for most parasites (even macroparasites, with a few exceptions such as fish monogenes), it would be difficult to label anything as exotic. We therefore feel that this group should be given low priority at present.

B. Other recommendations

The increasing importance of aquarium releases, recreational boating and fishing, and similar vectors bringing freshwater species to the Delta has received relatively little management attention, particularly compared to that addressed to ballast water. Some of the most expensive and troublesome invaders in the Delta, the aquatic plants, have been almost exclusively released by individual aquarists and backyard pond hobbyists. The most recently documented Delta invader, the New Zealand mud snail, was an apparent hitchhiker on recreational fishing gear; this species has attracted considerable management concern due to its high abundances and negative impacts in other invaded systems. If zebra mussels, perhaps our most-feared potential invader, ever reach the Delta, they will probably arrive as hitchhikers as well. These examples, along with the overall trend, suggest a need for increased attention to this category of introduction vectors. Education of aquarium hobbyists, gardeners, fishers and boaters, as well as development of appropriate, cost-effective regulation of trade in exotic species (Padilla & Williams 2004) will be required to address this increasingly important vector of invasions into the SSJR.

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APPENDIX A: Database description

General information

The relational database (DeltaInvasions) was developed in Microsoft ACCESS 2000 (version 9.0.2719). It was based (in part) on two models: the SERC_Invasions database of the National Ballast Water Clearinghouse (Smithsonian Ecological Research Center 2003), and the LCRANSdb database of the Lower Columbia River NAS Survey (Draheim Waldeck et al. 2003). At the time of development, we had access to the table structure only of the SERC_Invasions database. While we have attempted to make our database compatible with SERC's, particularly by using common codes and ecological terms, we used a simplified table structure more suited to our objectives for the current project.

Currently, the database contains information on all known or suspected NAS identified from the literature search as occuring in the Sacramento-San Joaquin Delta (as described in the Introduction to this report). It could relatively easily be extended to include species from the lower San Francisco Estuary as well, and to include native as well as nonindigenous and cryptogenic species.

Accessing and entering data using the main DeltaSpecies form

The simplest way to view data on individual species, and to enter new species information, is by using the form DeltaSpecies. This form has been set to open automatically when the database is launched. Taxonomic fields, including scientific and common names, can be searched with the "find" function. **To enter new data:** click ▶✳ at the bottom of the form to begin a new record. Note that the ScientificName field updates the table DeltaTaxonomy. Attempting to add a species already in this table (which includes some lower estuary invaders and nearby invaders) will result in an error message. If you get this message, add the species to the DeltaSpecies table first. **Sorting:** The form is currently set to sort taxonomically by major group, then alphabetically by species; certain modifications may cause it to default to sorting by SpeciesID number (approximately alphabetically). To re-establish the taxonomic sort, choose Records: Apply Filter/Sort. If this doesn't work, you need to re-load the desired sort order. Choose Records: Filter: Advanced Filter/Sort, then right-click anywhere on the page and choose "Load from Query". Choose "qryDeltaSpeciesSort", then right-click again and choose "Apply Filter/Sort".

Other forms

DeltaReferences: Use this form to enter new references or view full reference information, including abstract, cited species, etc. **Note:** References must be entered here (or directly into the DeltaReferences table) before citation information can be entered in the DeltaSpecies form.

Subforms: Typically these will be accessed via one of the main forms. Access them directly only if modifications to the structure of the subform are needed.

Tables

DeltaCollections contains collection information for certain benthic species. This table was a late addition to the database to facilitate future expansion, and therefore is not complete. Included information is from the IEP benthic database (IEP 2003). Further information from this database is needed, as well as collection information from the more dispersed literature.

Collection site information (at least a station code) must first be entered in the DeltaStations table. (All current and historic IEP benthos, zooplankton, and phytoplankton stations should be in this table already.) Collections information can then be entered directly into the table or into the subform located on the "Collections" tab of the DeltaSpecies form.

DeltaHabitats contains habitat information for each NAS species and some cryptogenic species. Multiple records may be entered for each species if different life stages occupy different habitats. Data can be entered via the subform located on the "Habitats" tab of the DeltaSpecies form.

DeltaNearbyInvaders contains abbreviated information on NAS found in areas adjacent to the Delta, which may be expected in the Delta in the future (or may have been overlooked there). To add new species to this list, add them to the table DeltaTaxonomy first.

DeltaOtherRegions contains information and citations relating to other locations where each species has been introduced. This table is not comprehensive—records were entered as they were encountered, but for most species no extensive effort was made to track down introduction records, particularly for sites outside the United States.

DeltaReferences contains full information on all references cited in other tables. All species referred to appear in the subdatasheet (and species information can be added here). References can be entered most easily using the DeltaReferences form.

DeltaSpecies contains the majority of the species-level information on NAS found in the Sacramento-San Joaquin Delta, including basic taxonomic information, population status, invasion history, ecology, impacts, and general distribution. Citations to references for each species appear in the subdatasheet accessible by clicking the "+" on the far left of the record. Data can be entered into this table most easily using the DeltaSpecies form.

DeltaSpecies-referenceLinks is a junction table linking references to cited species in both the DeltaSpecies and DeltaNearbyInvaders tables.

DeltaStations contains site information, including verbal descriptions and latitude/longitude, for collection sites referenced in tblDeltaCollections. Currently this table contains information only for IEP Environmental Monitoring Program sites. Site information (at least a site code) must be added to this table before collection information is entered into the DeltaCollections table or subform.

DeltaTaxonomicGroups contains common names for the major taxonomic groups of Delta NAS. When adding new groups, maintain taxonomic sort order by assigning an appropriate group code (may be decimal if necessary to insert between existing groups).

DeltaTaxonomy is the central location for all species names (including some lower estuary invaders and nearby invaders), and contains full taxonomic information for NAS and cryptogenic species found in the Delta. Update species names, spelling and taxonomic information in this table. (This can also be done via the DeltaSpecies form for Delta NAS.)

APPENDIX B: Delta NAS

Following is the list of species determined to be definite or probable invaders in the Sacramento-San Joaquin Delta, giving general salinity habitat, dates first recorded in the Delta and in central California, native region (if known) and probable invasion vector(s). The full names for vector abbreviations are given at the end of the table.

Scientific Name	Common Name	Salinity habitat	Date first recorded: Delta	Central CA	Native Region	Vector	
Plants (dicots)							
Apium graveolens	wild celery	Fresh	1892	1882	Eurasia	EC	
Bacopa rotundifolia	disc waterhyssop	Fresh	1998*	1949*	North America	AW	
Bidens vulgata	big devils beggartick	Fresh	1893	1893	e N America	UnkV	
Boehmeria cylindrica	smallspike false nettle	Fresh	2000	2000	e and c N America	UnkV	
Cabomba caroliniana	Carolina fanwort	Fresh	1980	1980	e N America	PR	
Chenopodium macrospermum var. halophilum	saltloving goosefoot	Estuarine-regular in Delta	1923	1923	South America	UnkV	
Conium maculatum	poison hemlock	Fresh	1979	1892	Europe	GE	
Cotula coronopifolia	brassbuttons	Estuarine-regular in Delta	1979*	1878	s Africa	DrB	
Elatine ambigua	Asian waterwort	Fresh	1979-8	1946	e & s Asia	AW	
Hypericum mutilum	dwarf St. John's wort	Fresh	1957*	1957	e N America	GE	AW
Lepidium latifolium	perennial pepperweed	Fresh	1941	1936	Eurasia	AW	
Limosella australis	Welsh mudwort	Fresh	1957	1957	e N America	UnkV	DrB
Ludwigia peploides ssp. montevidensis	floating primrose-willow	Fresh	1949	1916	s S America	GE	
Lythrum hyssopifolia	hyssop loosestrife	Fresh	1890	1879	Eurasia	GE	AW
Lythrum tribracteatum	threebract loosestrife	Fresh	1930	1930	s Europe	GE	AW
Mentha piperita	peppermint	Fresh	1979*	1892	Europe	EC	
Mentha aquatica	water mint	Fresh	1984*	1957	Europe	EC	
Mentha pulegium	pennyroyal	Fresh	1888	1887	Europe	EC	
Mentha spicata	spearmint	Fresh	1991*	1891	Europe	EC	
Myriophyllum aquaticum	parrotfeather	Fresh	1979*	1957*	S America	EC	PR
Myriophyllum spicatum	Eurasian water-milfoil	Fresh	1979	1976	Eurasia	PR	
Phyla nodiflora	turkey tangle fogfruit	Fresh	1934*	1864	S America	ErC	
Plantago major	common plantain	Fresh	1891	1891	Europe	AW	EC
Polygonum hydropiper	marshpepper	Fresh	1891	1891	Europe	EC	
Polygonum patulum	Bellard's smartweed	Fresh	1893	1893	e Europe	UnkV	EC
Polygonum persicaria	lady's-thumb	Fresh	1934	1888	Europe	GE	
Pseudognaphalium luteoalbum	Jersey cudweed	Fresh	1991	1928	Europe	AW	EC
Ranunculus muricatus	spinyfruit buttercup	Fresh	1979-8	1882	Europe (Mediterranean to	GE	AW
Rorippa nasturtium-aquaticum	watercress	Fresh	1890	1885	Europe	EC	

Scientific Name	Common Name	Salinity habitat	Date first recorded: Delta	Central CA	Native Region	Vector		
Plants (dicots)								
Rubus discolor	Himalayan blackberry	Fresh	1979-8	1919	Armenia	EC		
Rumex conglomeratus	clustered dock	Fresh	1890	1890	Europe	AW	EC	
Rumex crispus	curly dock	Fresh	1895	1887	Eurasia	AW	EC	
Rumex dentatus	toothed dock	Fresh	1893	1893	Eurasia	AW		
Rumex obtusifolius	bitter dock	Fresh	1989*	1907	w Europe	AW	EC	
Rumex stenophyllus	narrowleaf dock	Fresh	1990	1948	Eurasia	AW	EC	
Salix babylonica	weeping willow	Fresh	1980	1905	Asia	GE		
Sesbania punicea	scarlet wisteria tree	Fresh	1999	1994	S America	GE		
Spergularia maritima	media sandspurry	Estuarine-regular in Delta	1979	1951	Europe	UnkV	DrB	
Tamarix ssp.	tamarisk	Fresh	1928	1895	Eurasia	EC	GE	ErC
Verbena bonariensis	purpletop vervain	Fresh	1996	1938	S America	GE		
Veronica anagallis-aquatica	water speedwell	Fresh	1971*	1881	Europe	UnkV	GE	
Plants (monocots)								
Agrostis avenacea	Pacific bentgrass	Fresh	1946	1935	s Pacific Islands	UnkV	EC	
Agrostis gigantea	redtop	Fresh	1996*	1970*	Europe	EC		
Agrostis stolonifera	creeping bentgrass	Fresh	1996*	1896	Europe and North Africa	EC		
Agrostis tandilensis	Kennedy's bentgrass	Fresh	1979-8	1958	Argentina	UnkV	EC	
Alisma lanceolatum	lanceleaf water plantain	Fresh	1985*	1946	Eurasia, N Africa	GE		
Arundo donax	giant reed	Fresh	1980	1949	India	ErC	EC	
Crypsis alopecuroides	pricklegrass	Fresh	2002-0	2001	Europe	AW		
Crypsis schoenoides	swamp prickle grass	Fresh	1940	1940	Europe	UnkV	EC	
Crypsis vaginiflora	African pricklegrass	Fresh	1907	1898	Mediterranean	UnkV	AW	
Cyperus difformis	variable flatsedge	Fresh	1998*	1921	Asia and Africa	AW		
Echinochloa crus-galli	barnyard grass	Fresh	1930	1891	Eurasia and Africa	AW		
Echinochloa crus-pavonis	gulf cockspur grass	Fresh	1893	1893	Eurasia and Africa	AW		
Echinochloa oryzoides	early water grass	Fresh	1953	1953	Eurasia	AW		
Egeria densa	Brazilian waterweed	Fresh	1946	1938	Argentina, Brazil, and Uruguay	PR		
Eichhornia crassipes	water hyacinth	Fresh	1904	1904	Amazon River basin	GE		
Hainardia cylindrica	barbgrass	Fresh	1979-8	1896	Europe	UnkV		
Iris pseudacorus	yellow iris	Fresh	1969	1957	Europe	GE		
Panicum rigidulum var.	redtop panicgrass	Fresh	1972*	1950	e N America	UnkV		
Polypogon elongatus	streambank rabbitsfoot	Fresh	1897	1897	S America	AW		
Polypogon interruptus	ditch rabbitsfoot grass	Fresh	1992-9	1885	S America	AW		
Polypogon maritimus	Mediterranean beard grass	Fresh	1979-8	1892	Mediterranean Europe and	AW		
Polypogon monspeliensis	annual rabbitsfoot grass	Fresh	1904	1882	Europe	AW		

Scientific Name	Common Name	Salinity habitat	Date first recorded: Delta	Central CA	Native Region	Vector		
Plants (monocots)								
Polypogon viridis	water bent	Fresh	1928	1896	Europe	AW		
Potamogeton crispus	curly pondweed	Fresh	1946	1946	Europe	FA		
Schoenoplectus glaucus	tuberous bulrush	Fresh	2003*	1948	Europe	EC	AW	
Schoenoplectus mucronatus	ricefield bulrush	Fresh	2003*	1946	Eurasia	AW		
Setaria sphacelata	African bristlegrass	Fresh	1979-8	1904	Africa	UnkV		
Typha angustifolia	narrow-leafed cattail	Fresh	1909	1909	Europe	UnkV		
Invertebrates								
Annelida								
Branchiobdellida								
Cambarincola sp.	crayfish worm	Fresh	1979	1979	e N America or Pacific NW	FA		
Hirudinea								
Myzobdella lugubris	ectoparasite of catfish	Fresh	1975*	1975*	e N America	FA		
Oligochaeta								
Branchiura sowerbyi		Fresh	1950	1950	India, Manmar, Java, China,	BW	DrB	AP
Paranais frici		Fresh	1973	1961	Europe	BW	DrB	AP
Potamothrix bavaricus		Fresh	1991	1965	Europe	BW	DiB	AP
Potamothrix sp. A		Fresh	1998	1998	Europe?	BW	DiB	AP
Tubificoides brownae		Estuarine-rare in Delta	1992	1961	n Atlantic	DrB	BW	OA
Varichaetadrilus angustipenis		Fresh	1975*	1975	e N America	BW	AP	
Polychaeta								
Amaeana sp.		Estuarine-rare in Delta	2001	1999	unknown	BW		
Boccardiella ligerica		Estuarine-regular in Delta	1977	1954	w Europe	BW		
Heteromastus filiformis		Estuarine-rare in Delta	1936	1936	e N America	OA	BW	
Laonome sp.		Fresh	1989	1989	unknown	BW		
Manayunkia speciosa		Fresh	1963*	1963*	e N America	FA	BW	
Marenzelleria viridis		Fresh	1991	1991	e N America	BW		
Neanthes succinea	pile worm	Estuarine-rare in Delta	1896	1896	e N America	OA	FC	BW
Streblospio benedicti		Estuarine-rare in Delta	1986	1932	western and eastern Atlantic	BW	OA	FC
Typosyllis sp.		Estuarine-rare in Delta	1998	1997	Japan	BW		

Scientific Name	Common Name	Salinity habitat	Date first recorded: Delta	Central CA	Native Region	Vector	
Mollusca							
Gastropoda							
Cipangopaludina chinensis malleata	Chinese mysterysnail	Fresh	1938	1892	China, Japan	RI	
Melanoides tuberculata	red-rim melania	Fresh	1988	1988	Africa to east Indies	PR	
Philine auriformis	tortellini snail	Estuarine-rare in Delta	2001	1992	New Zealand	BW	
Potamopyrgus antipodarum	New Zealand mud snail	Fresh	2003	2003	New Zealand	RecB	
Bivalvia							
Corbicula fluminea	Asian clam	Fresh	1945	1945	China, Korea, Japan	RI	
Macoma petalum	Baltic clam	Estuarine-rare in Delta	1988	~1869	nw Atlantic	OA	DrB
Musculista senhousia	Japanese mussel	Estuarine-rare in Delta	1946	1941	Japan, China	OA	
Mya arenaria	soft-shell clam	Estuarine-rare in Delta	1874	1874	e N America	OA	
Potamocorbula amurensis	Amur river corbula	Estuarine-regular in Delta	1986	1986	s China to s Siberia, Japan	BW	
Venerupis philippinarum	Japanese littleneck clam	Estuarine-rare in Delta	1946	1930	w Pacific	OA	
Arthropoda							
Ostracoda							
Eusarsiella zostericola		Estuarine-rare in Delta	1994*	1953*	nw Atlantic	OA	
Cladocera							
Daphnia lumholtzi	daphnia	Fresh	1999	1999	Africa, Asia, Australia	RecB	
Copepoda							
Acartiella sinensis		Estuarine-regular in Delta	1993	1993	China	BW	
Eurytemora affinis		Estuarine-regular in Delta	1912	1912	e N America	FA	
Lernaea cyprinacea	Lernaea	Fresh	1975*	1975*	Asia	FA	PR
Limnoithona sinensis		Fresh	1979	1979	Yangtze River, China	BW	
Limnoithona tetraspina		Estuarine-regular in Delta	1993	1993	Yangtze River, China	BW	
Oithona davisae		Estuarine-rare in Delta	1979	1979	Japan	BW	
Pseudodiaptomus forbesi		Fresh	1987	1987	Yangtze River, China	BW	
Pseudodiaptomus marinus		Estuarine-rare in Delta	1986	1986	China, Japan	BW	OA
Sinocalanus doerrii		Fresh	1978	1978	Chinese rivers	BW	
Tortanus dextrilobatus		Estuarine-regular in Delta	1993	1993	Korea, China	BW	
Cirripedia							
Balanus improvisus	bay barnacle	Estuarine-regular in Delta	1853	1853	e N America	FC	OI

Scientific Name	Common Name	Salinity habitat	Date first recorded: Delta	Central CA	Native Region	Vector		
Mysidacea								
Acanthomysis aspera		Estuarine-rare in Delta	1992	1992	Japan	BW		
Acanthomysis bowmani		Estuarine-regular in Delta	1993	1993	e Asia	BW		
Acanthomysis hwanhaiensis		Estuarine-rare in Delta	1997	1997	Korea	BW		
Deltamysis holmquistae		Estuarine-rare in Delta	1977	1977	unknown	BW		
Cumacea								
Nippoleucon hinumensis		Estuarine-regular in Delta	1986	1986	Japan	BW		
Isopoda								
Asellus hilgendorfii		Fresh	1978	1978	China, Japan, Siberia	BW		
Caecidotea racovitzai		Fresh	1999	1999	ne N America	BW	AP	
Iais californica		Estuarine-rare in Delta	1904*	1904*	Australia, New Zealand	FC		
Munna sp. A		Fresh	1989	1989	unknown	UnkV		
Sphaeroma quoyanum		Estuarine-rare in Delta	1893	1893	Australia, New Zealand,	FC		
Synidotea laevidorsalis		Estuarine-regular in Delta	1897	1897	e Asia	FC		
Tanaidacea								
Sinelobus stanfordi		Estuarine-regular in Delta	1943	1943	unknown	FC	BW	
Amphipoda								
Ampelisca abdita		Estuarine-rare in Delta	1954	1954	nw Atlantic	BW	OA	
Corophium alienense		Estuarine-regular in Delta	1973	1973	Southeast Asia?	BW		
Crangonyx floridanus		Fresh	1998	1998	e & e-c N America	BW	AP	
Gammarus daiberi		Estuarine-regular in Delta	1983	1983	e N Atlantic	BW	AP	FC
Grandidierella japonica		Estuarine-regular in Delta	1976	1966	Japan	OA	BW	FC
Melita nitida		Estuarine-regular in Delta	1938	1938	e N America	FC	OA	DrB
Monocorophium acherusicum		Estuarine-regular in Delta	1912	1912	uncertain	OA	FC	
Monocorophium insidiosum		Estuarine-rare in Delta	1931	1931	n Atlantic	FC	OA	
Parapleustes derzhavini		Estuarine-rare in Delta	1977	1904	e Asia	FC		
Decapoda								
Exopalaemon modestus	Asian freshwater shrimp	Fresh	2001	2001	Russia, Korea, China, Taiwan	BW		
Palaemon macrodactylus	oriental shrimp	Estuarine-regular in Delta	1957	1957	Korea, Japan, N China	BW	FC	
Orconectes virilis	virile crayfish	Fresh	1959	1940	mw N America	SE		
Pacifastacus leniusculus	signal crayfish	Fresh	1959	1912	nw N America	FI		
Procambarus clarkii	red swamp crayfish	Fresh	1959*	1959*	se US	RI		
Eriocheir sinensis	Chinese mitten crab	Estuarine-regular in Delta	1996	1992	China, Korea	RI	BW	
Rhithropanopeus harrisii	Harris mud crab	Estuarine-regular in Delta	1975	1937	e N America	OA	FC	BW

Scientific Name	Common Name	Salinity habitat	Date first recorded: Delta	Date first recorded: Central CA	Native Region	Vector	
Insecta							
Neochetina bruchi	chevroned water hyacinth weevil	Fresh	1982	1982	Argentina	BC	
Neochetina eichhorniae	mottled water hyacinth weevil	Fresh	1982	1982	Argentina	BC	
Miscellaneous Phyla							
Myxozoa							
Myxobolus koi	parasite of carp	Fresh	1975*	1975*	Japan	FA	
Cnidaria							
Blackfordia virginica		Estuarine-regular in Delta	2001	1970	Black Sea, Europe	BW	FC
Cordylophora caspia	freshwater hydroid	Fresh	1950*	1950*	Black and Caspian Seas	FC	BW
Craspedacusta sowerbii	freshwater jellyfish	Fresh	1953	1953	China	AP	PR
Maeotias marginata	Black Sea jellyfish	Estuarine-regular in Delta	1981*	1981*	Black and Caspian Seas	BW	FC
Moerisia sp.		Estuarine-rare in Delta	1997	1993	Eurasia or North Africa	BW	FC
Platyhelmithes							
Alloglossidium corti	trematode parasite of catfishes	Fresh	1968*	1968*	e N America	FA	
Atractolytocestus huronensis	cestode parasite of cyprinids	Fresh	1975*	1975*	unknown	FA	
Bothriocephalus claviceps	cestode parasite of sunfishes	Fresh	1968*	1968*	e N America	FA	
Corallobothrium fimbriatum	cestode parasite of catfishes	Fresh	1968	1968*	e N America	FA	
Dactylogyrus extensus	trematode parasite of carp	Fresh	1975*	1975*	Eurasia	FA	
Khawia iowensis	cestode parasite of carp	Fresh	1975*	1975*	unknown	FA	
Ligictaluridus pricei	trematode parasite of catfishes	Fresh	1975*	1975*	e N America	FA	
Megathylacoides giganteum	cestode parasite of catfishes	Fresh	1968*	1968*	e N America	FA	
Pisciamphistoma stunkardi	trematode parasite of sunfishes	Fresh	1968*	1968*	e N America	FA	
Nematoda							
Capillaria catenata	nematode parasite of fishes	Fresh	1975*	1975*	e N America	FA	
Hysterothylacium brachyurum	nematode parasite of fishes	Estuarine-regular in Delta	1975*	1975*	e N America	FA	
Philometroides sanguinea	nematode parasite of goldfish	Fresh	1975*	1975*	Japan	FA	
Entoprocta							
Urnatella gracilis	freshwater entoproct	Fresh	1982	1972	e & mw N America	AP	PR

Scientific Name	Common Name	Salinity habitat	Date first recorded: Delta	Central CA	Native Region	Vector		
Vertebrates								
Fishes								
Acanthogobius flavimanus	yellowfin goby	Estuarine-regular in Delta	1963	1963	Japan, Korea, China	BW	FC	
Alosa sapidissima	American shad	Estuarine-regular in Delta	1871	1871	e N America	FI		
Ameiurus catus	white catfish	Fresh	1874	1874	e N America	FI		
Ameiurus melas	black bullhead	Fresh	1952*	1931	e N America	FI		
Ameiurus nebulosus	brown bullhead	Fresh	1874	1874	c N America	FI		
Carassius auratus	goldfish	Fresh	1963*	1863	Asia	PR		
Cyprinella lutrensis	red shiner	Fresh	1994	1954	c N America	DiB	FI	
Cyprinus carpio	common carp	Fresh	1883	1972	Eurasia	FI		
Dorosoma petenense	threadfin shad	Fresh	1961	1959	c and se N America, C America	FI		
Gambusia affinis	western mosquitofish	Fresh	1924-1	1922	c and se N America	BC		
Hypomesus nipponensis	wakasagi	Fresh	1990*	1959	Japan	FI		
Ictalurus furcatus	blue catfish	Fresh	1978	1978	c and se N America	AQ	FI	
Ictalurus punctatus	channel catfish	Fresh	1943	1942	c N America	FI		
Lepomis cyanellus	green sunfish	Fresh	1896	1896	Mississippi drainage	FI	FA	
Lepomis gibbosus	pumpkinseed	Fresh	1980	1983	e N America	FI		
Lepomis gulosus	warmouth	Fresh	1941*	1891	c and se N America	FI		
Lepomis macrochirus	bluegill	Fresh	1909-1	1908	c and se N America	FI		
Lepomis microlophus	redear sunfish	Fresh	1956	1956	c and se N America	FI		
Lucania parva	rainwater killifish	Estuarine-regular in Delta	1958	1958	e and s N America	OA	BW	FA
Menidia beryllina	inland silverside	Fresh	1971	1967	se N America	BC		
Micropterus coosae	redeye bass	Fresh	1999*	1962	se N America	FI		
Micropterus dolomieu	smallmouth bass	Fresh	1898-9	1874	c N America	FI		
Micropterus punctulatus	spotted bass	Fresh	2002	1937	c and se N America	FI		
Micropterus salmoides	largemouth bass	Fresh	1909	1891	c N America	FI		
Morone saxatilis	striped bass	Estuarine-regular in Delta	1879	1879	e N America	FI		
Notemigonus crysoleucas	golden shiner	Fresh	1940*	1891	e and c N America	FI		
Percina macrolepida	bigscale logperch	Fresh	1970	1953	sw N America	FA		
Pimephales promelas	fathead minnow	Fresh	1953	1953	c N America	FI		
Pomoxis annularis	white crappie	Fresh	1963-6	1951	c and se N Amer	FI		
Pomoxis nigromaculatus	black crappie	Fresh	1931	1908	c and se N America	FI		
Tridentiger barbatus	shokihaze goby	Estuarine-regular in Delta	1997	1997	Japan, Korea, China	BW		
Tridentiger bifasciatus	shimofuri goby	Estuarine-regular in Delta	1985	1985	e Asia	BW		

Scientific Name	Common Name	Salinity habitat	Date first recorded: Delta	Central CA	Native Region	Vector	
Amphibians							
Rana catesbeiana	bullfrog	Fresh	1933	1896	e N America	AQ	SE
Reptiles							
Trachemys scripta	common slider	Fresh	1989*	1976*	se US	PR	
Mammals							
Ondatra zibethicus	muskrat	Fresh	1943	1930s	e N America	AQ	

Vectors: AQ-Aquaculture escape , AW-Agricultural Weed, BC-Biocontrol release, BW-Ballast Water, DiB-Discarded Bait, DrB-Dry Ballast, EC-Escape from cultivation, ErC-Erosion Control, FA-Fisheries Accidental (not Oyster), FC-Fouling Community, FI-Fisheries Intentional, GE-Garden Escape, OA-Oyster Accidental, OI-Oyster Intentional, PR-Pet/Aquarium Release, RecB-Recreational Boating/Fishing, RI-Released by Individual, SE-Scientific Escape, UnkV-Unknown.
*indicates dates which probably differ by 10 or more years from the actual invasion date.

APPENDIX C: Cryptogenic Species in the Delta

The following table lists species determined to cryptogenic in the Sacramento-San Joaquin Delta.

ScientificName	CommonName
Microalgae	
Anabaena sp.	blue-green alga
Oscillatoria sp.	blue-green alga
Nitzschia sp.	diatom
Aulacoseira spp.	diatom
Chaetoceros spp.	diatom
Coscinodiscus spp.	diatom
Cyclotella spp.	diatom
Asterionella sp.	diatom
Achnanthes sp.	diatom
Biddulphia spp.	diatom
Navicula spp.	diatom
Pleurosigma sp.	diatom
Rhizosolenia sp.	diatom
Skeletonema sp.	diatom
Thalassiosira sp.	diatom
Gymnodinium sp.	dinoflagellate
Scenedesmus sp.	chlorophyceae
Vascular plants	
Phalaris arundinacea	reed canarygrass
Invertebrates	
Prostoma graecense	freshwater ribbon worm
Synchaeta bicornis	rotifer
Aulodrilus limnobius	oligochaete
Bothrioneurum vejdovskyanum	oligochaete
Limnodrilus udekemianus	oligochaete
Limnodrilus hoffmeisteri	oligochaete
Grandifoxus grandis	amphipod

APPENDIX D: Nearby Invaders

The following table lists NAS found in areas adjacent to the Sacramento-San Joaquin Delta.

ScientificName	CommonName	Date	SourceRegion	Vector
Dicots				
Callitriche stagnalis	pond water-starwort			
Polygonum pensylvanicum	pinkweed, Pennsylvania smartweed		e N America	Escape from cultivation
Nymphaea odorata	fragrant waterlily, American white waterlily		e N America	Garden Escape
Nymphaea mexicana	yellow waterlily, banana waterlily		se N America, Mexico	Garden Escape
Lythrum salicaria	purple loosestrife	1968	Europe	Dry Ballast
Rotala indica	Indian toothcup			
Monocots				
Najas gracillima	thread-leaved water nymph, slender water nymph		e N America	Agricultural Weed
Aponogeton distachyos	Cape pondweed		s Africa	Pet/Aquarium Release
Eleocharis pachycarpa	black sand spikerush		Chile	
Fimbristylis miliacea	grasslike fimbry	1866	Eurasia	Agricultural Weed
Heteranthera limosa	blue mudplantain, ducksalad		e & c N America	Agricultural Weed
Hydrilla verticillata	hydrilla, waterthyme, Florida elodea	1976	Eurasia & central Africa	Pet/Aquarium Release
Monochoria vaginalis	heartshape false pickerelweed			Agricultural Weed
Najas graminea	rice-field water-nymph		Asia	Agricultural Weed
Ottelia alismoides	ducklettuce		Africa, India, sw Pacific	Agricultural Weed
Peltandra virginica	tuckahoe, green arrow arum		e N America	
Gastropods				
Planorbella duryi	seminole rams-horn		Florida	Pet/Aquarium Release
Pseudosuccinea columella	mimic limnaea	1921	e N America	
Radix auricularia	big-eared radix	1922	Europe	Pet/Aquarium Release
Fishes				
Esox lucius	northern pike	1994	e N America	Released by Individual
Morone chrysops	white bass	1987	e N America	Released by Individual
Reptiles				
Apalone spinifera	spiny softshell turtle	1998	e N America	Pet/Aquarium Release
Nerodia fasciata fasciata	southern water snake	1992	e N America	Pet/Aquarium Release
Graptemys pseudogeographica	false map turtle	1994	e N America	Pet/Aquarium Release
Pseudemys spp.	cooter	1994	e N America	Pet/Aquarium Release
Chrysemys picta	painted turtle	1997	e & c N America	Pet/Aquarium Release
Chelydra serpentina	snapping turtle	1976	e N America	Pet/Aquarium Release